Advanced Packaging for 5G in RF and Analog Mixed Signal

IEEE HIR 5G mm-waves TWG Chair
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Timothy Lee, currently a Boeing Technical Fellow, is responsible for the development of RF and digital electronics for advanced communications networks and sensor systems. In the IEEE, Tim is promoting the use of technology to benefit humanity.
Technology Roadmaps to Enable the 5G Ecosystem

• Microwave / millimeter-wave RF-Front Modules needed for emerging 5G User Equipment (UE) and Base-stations (BS)

• Roadmaps for Hardware and Advanced Packaging to guide us to areas of research for millimeter-wave RF Front-Ends for 5G and Beyond

• Time horizons: 3-, 5- and 10-years

• Addressing Semiconductors and Advanced Packaging technical trades

• Devices, materials, processes and substrates needed to support the goal of low-cost high performance 5G New Radio (NR) hardware

• Initial look at beyond 5G for technology needs between 100 GHz to 1 THz (6G)
## The Mobile Economy

### Unique mobile subscribers
- **2022:** 5.4bn
- **2030:** 6.3bn
- **Penetration rate:**
  - 68% in 2022
  - 73% in 2030
  - CAGR: 2.0%

### Mobile internet users
- **2022:** 4.4bn
- **2030:** 5.5bn
- **Penetration rate:**
  - 55% in 2022
  - 64% in 2030
  - CAGR: 4.5%

### SIM connections (excluding licensed cellular IoT)
- **2022:** 8.4bn
- **2030:** 9.8bn
- **Penetration rate:**
  - 105% in 2022
  - 114% in 2030
  - CAGR: 1.7%

### Smartphones
- **2022:** 76%
- **2030:** 92%

### Licensed cellular IoT connections
- **2022:** 2.5bn
- **2030:** 5.3bn

### Operator revenues and investment
- **2022:** $1.07tn
- **2030:** $1.20tn

### Mobile industry contribution to GDP
- **2022:** $5.2tn (5% of GDP)
- **2030:** $6.0tn

### Employment
- **16 million jobs**
- Directly supported by the mobile ecosystem in 2022
- **12 million jobs**
- Supported indirectly

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[https://www.gsma.com/mobileeconomy/](https://www.gsma.com/mobileeconomy/)
Status of 5G Deployments in 2024 (GSMA Report)

The 5G Era has begun and gaining momentum!

- C-Band: 3.7GHz to 3.98GHz turned on in US

https://www.gsma.com/mobileeconomy/

AT&T 5G+ SpeedTest at CES 2024 in Las Vegas Convention Center (mm-waves)
Digital Connectivity: A Transformative Opportunity

• The events of the last three years, with a global health pandemic and the swift international pivot to digital delivery of goods, services, work, and play, have yielded unique insights into just how critical stable, broadband access is and will continue to be. While the global markets still face strong economic headwinds today, digital connectivity has accelerated as people, businesses, and governments pivoted strongly towards online communications, and we continue to see new internet devices and applications, growing broadband penetration into developing markets.

• We won’t rest until we live in a world where meaningful connectivity is a lived reality for everyone, everywhere.”

https://broadbandcommission.org/publication/state-of-broadband-2023/
Every 10 years a new generation of mobile communication

- **1G** (1980s): Voice Analogue
- **2G** (1990s): Mobile Voice Messaging ~28.8 kbps
- **3G** (2000s): Start of mobile broadband Information in hand ~14Mbps
- **4G** (2010s): Smartphone Apps/video ~225Mbps
- **5G** (2020s): Mobile broadband ~10Gbps
- **6G** (2030s): Divergence Internet-of-things Rise of M2M Traffic

Joint Comm & Sensing
- eMBB
- URLLC
- MM2M

Peak data rate >100Gbps
Extreme coverage
Pervasive connectivity
Holographic telepresence...

Nadine Collaert, imec, Emerging device and heterogenous integration technologies for sub-THz Applications, ISSCC 2022, 6G Forum.
Solutions needs to enable additional spectrum

- Sweet Spot still C-Band
- FR2 bands usage limited but growing
- 6G …

- Congested licensed bands below 6GHz
  - Best for range and transmission
  - Over $1 Trillion in Value!
- Coexistence challenges with WiFi
- FR3 slowly progressing through unwinding exiting allocations

- US C-band auction: $80B for 280 MHz
  - FR3 spectrum value will be large
- Huge amounts of spectrum available at 100-300 GHz
  - Solutions will be technically challenging

Source: Taro Eichler, Millimeterwave and THz Technology for 5G and Beyond, Rohde & Schwarz

Nicholas Comfoltey, “Emerging Device Technologies for RF/mmWave FEMs,” ISSCC2023 Forum
MmWave Development in 2023: Where's It Going & What Are the Challenges

Positives: 3 years after 5G was officially commercialized, while most of the deployments are primarily focused on 5G mid-band, the development of 5G mmWave technology has also been underway. 5G mmWave, operating in high-frequency bands between 24-100 GHz, offers faster data transfer rates, low latency, and higher bandwidth compared to the previous wireless technology.

Negatives: However, the deployment of 5G mmWave technology poses challenges beyond its physical characteristics, such as shorter range and susceptibility to interference.

• Lack of compelling business use cases that justify its cost and deployment challenges.
• The benefits may not be enough to justify the significant investment required to deploy it.
• Need to identify and prioritize the use cases to provide the most significant impact and return on investment.

Source: "5G Market 2023-2033: Technology, Trends, Forecasts, Players" from IDTechEx

FR2: FWA and high-density areas like stadiums and airports

Millimeter-Waves Challenges and Mitigations

Challenges:
- Propagation: Line of Sight
- Rain attenuation
- Foliage attenuation
- Building penetration losses

Mitigations:
- Phased Arrays
- Use of low-band for UL
- Use of High Power UE

AiP (Antenna-in-Package) subsystem is designed for both gNB and UE to eliminate mmWave propagation loss as well as reduce the path loss from the antenna to the baseband to improve the receiving sensitivity.

6G Wireless Communications in 7–24 GHz Band: Opportunities, Techniques, and Challenges

Emergence of FR3:

Why mmWave?

Shannon-Hartley Theorem:

\[
C = B \log_2 \left( 1 + \frac{P}{N_0 B} \right)
\]

- \(C\): Channel capacity
- \(B\): Channel Bandwidth [Hz]
- \(N_0\): Noise Power Spectral Density [W/Hz]
- \(P\): Average Received Power [W]

High SNR: Capacity is **linear in bandwidth**, logarithmic in power.

Low SNR: Capacity is insensitive to bandwidth, **linear in power**.

<table>
<thead>
<tr>
<th>Carrier Frequency</th>
<th>Modulation</th>
<th>Available Bandwidth [GHz]</th>
<th>Max Data Rate [Gb/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sub-6GHz</td>
<td>4096-QAM</td>
<td>0.15</td>
<td>1.35</td>
</tr>
<tr>
<td>28GHz</td>
<td>256-QAM</td>
<td>0.85</td>
<td>5.1</td>
</tr>
<tr>
<td>60GHz</td>
<td>64-QAM</td>
<td>8.64</td>
<td>38.9</td>
</tr>
<tr>
<td>70GHz</td>
<td>64-QAM</td>
<td>5</td>
<td>22.5</td>
</tr>
</tbody>
</table>

\(~30x\) increase in data rate!

Operation at mmWave frequencies enables wide bandwidth designs → **Potential** for higher data rates
RF Front-Ends Play a Critical Role to the Deployment of 5G Ecosystem (RFICs, Antennas and Advanced Packaging)

According to the Fact & Figures research report, the global 5G Smart Antenna Market in 2019 was approximately USD 260 million. The market is expected to grow at a CAGR of 57% and is anticipated to reach around USD 6,325 million by 2026.

5G RF Front-End Modules faces many design challenges

- **UE is highly SWaP-C constrained**
  - Battery Life
  - Mm-wave propagation losses
- **BS Challenges**
  - Signal Blockage
  - Output Power & PAE
  - Thermal
  - Yield & Affordability
- **Key Technologies:**
  - Advanced node CMOS, FD-SOI
  - 2.5D/3D packaging
  - Low-loss substrates
Main Design Challenges for End-to-End, Full-Stack THz Networks

Link design for ultra-high bandwidth
Medium access and retransmissions design

Scheduled access
Contention-based access
Introducing awareness
Directional neighbor and infrastructure discovery

Make the network scale
Deploy energy-aware protocols and network nodes

Managing the spectrum
Optimize spectrum allocation and manage interference

Move bits end-to-end
Backhaul and transport protocol design

Heterogeneous Integration Platform

<table>
<thead>
<tr>
<th>Substrate Core</th>
<th>Silicon</th>
<th>Organic</th>
<th>Glass</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Laminates</td>
<td>Fanout (Epoxy Mold Compound)</td>
</tr>
<tr>
<td>Material properties</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Surface roughness (nm)</td>
<td>&lt;10</td>
<td>400-600</td>
<td>&gt; 1000</td>
</tr>
<tr>
<td>CTE (ppm/K)</td>
<td>2.9-4</td>
<td>3-17</td>
<td>16-30</td>
</tr>
<tr>
<td>Young’s modulus (GPa)</td>
<td>165</td>
<td>10-40</td>
<td>22</td>
</tr>
<tr>
<td>Moisture absorption</td>
<td>0</td>
<td>0.04%</td>
<td>1.25%</td>
</tr>
<tr>
<td>Thermal conductivity (W/m.K)</td>
<td>148</td>
<td>0.9</td>
<td>0.5-0.75</td>
</tr>
</tbody>
</table>

| Physical Dimensions |         |       |       |       |
| Package size (mm) | 35x35 | 70x70 | 50x50 | 100x100 |
| Panel/Wafer size | 300 mm | 710 mm² | 300 mm / 510 mm² | 710 mm² |

- Materials with Silicon like properties that maximize chip and board level reliability and support larger body sizes required!
- CTE in the range of 7-9 ppm/K with low surface roughness, Young’s Modulus and zero moisture absorption required.
- Glass Interposer is a good candidate!

Madhavan Swaminathan, “Packaging for mmWave Communications,” March 2021, INEMI Webinar
Mm-wave Phased Arrays: a Common Feature in your Phone!

5G Antenna Modules in Samsung S20 Ultra


Iphone 13 Pro mm-wave modules / antenna and 5G Modem

Technology/Capability Gaps and Showstoppers

**Challenge 1: Tight Integration is Needed for mm-wave Phased Arrays**

<table>
<thead>
<tr>
<th>Frequency</th>
<th>Element Spacing</th>
<th>Dual Pole I/O Spacing</th>
</tr>
</thead>
<tbody>
<tr>
<td>3 GHz</td>
<td>50 mm, 2 inches</td>
<td>25 mm, 1 inch</td>
</tr>
<tr>
<td>10 GHz</td>
<td>15 mm, 600 mils</td>
<td>7.5 mm, 300 mils</td>
</tr>
<tr>
<td>30 GHz</td>
<td>5 mm, 200 mils</td>
<td>2.5 mm, 100 mils</td>
</tr>
</tbody>
</table>

At 30 GHz, \( \lambda/2 \approx 200 \text{ mils}, \text{ or } 5 \text{ mm} \\
Electronic footprint a serious challenge \\
- Worse for dual pole \\
- Front-end function desired in beamformer package \\
- PAs and LNAs

6G ➔ 140 GHz ➔ 1mm

5G Front-End architecture (number of elements, EIRP, Si vs III-V, and Packaging) need to be tailored for each use case
Phased Arrays are a key enabler for mmWave

- Link budget improves $30\log_{10}(N)$
- For a phased array of $N$ elements
  - Tx array: focused Tx radiation energy
    - TRP increases by $10\log_{10}(N)$
    - EIRP increases by $20\log_{10}(N)$
  - Rx array: enhanced Rx sensitivity
    - $S/N$ increases $10\log_{10}(N)$
    - NF decreases by $10\log_{10}(N)$
- Beam width narrows $\sim 2\sin^{-1}(2/N)$
- Array area decreases $(l/2)^2$ ($l/2$ lattice spacing)

Lower Tx power per Power Amplifier and Antenna element

mmWave FEM requirements can be addressed by Silicon technologies

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International Solid-State Circuits Conference

F3.1: Emerging Device Technologies for RF/mmWave FEMs

Nicholas Comfoltey, “Emerging Device Technologies for RF/mmWave FEMs,” ISSCC2023 Forum
Key Antenna Package Requirements

**Electrical**
- Impedance matching at each port
- Radiate EM energy efficiently
- Achieve low coupling between antenna elements
- Have equal signal delays between input ports and antenna feedlines
- Achieve near hemi-spherical radiation patterns, equal among radiation elements
- Feature sufficient layers for IC interconnects

**Thermomechanical**
- Provide mechanical support to the ICs
- Achieve low CTE mismatch with the ICs for mechanical stability over temperature
- Reliable mechanical connection to ICs and boards

Challenges for Millimeter-Wave Design

1. IC design & modeling is difficult
   - Challenge: Modeling challenges (Graph showing frequency vs. gain with markers: HBT, HBT, HBT-HBT, HBT, HBT-HBT).

2. Antenna-package-IC integration is difficult
   - Challenge: Integration challenges: Antenna constrained by package, package constrained by IC & thermal (Diagram of 1st-level package tiles with embedded antenna and 2nd-level PCB).

3. Measurements are difficult
   - Challenge: Requires expensive specialized equipment and frequent calibration.

Substrate and Process Options

LTCC (Ceramic)
- Antenna feed line
- Ag paste (10 um thick, p < 3 m/square)
- GPS-GND
- GPS cavity
- Power
- GND
- BGA
- BGA pitch (450um)
- Low-speed signal

LCP-based MLO (Organic)
- M4: 25um, 0um
- M3: 25um, 0um
- M2: 25um, 0um
- M1: 25um, 0um
- LCP
- LE
- RF Ground & some LF Routing
- Most RF & LF Routing

PCB
- Antenna
- PCB

Wafer-level packaging
- Mold Compound
- Silicon-MMIC
- Redistribution Layer (Copper)
- Inter-Chip Interconnect
- Intra-Chip Interconnect
- Silver Ball (Sn-Ag-Cu)
- Note: antennas on separate substrate, not shown

Thin films on glass
- Copper
- Plated Conformal Vias
- 15-um
- 100-um
- Glass
- Polymer Dielectric Film

Quartz Superstrate
- 0.7 mm Superstrate antenna
- Quartz
- 2.8 mm Quartz thin film
- M6 Layer
- M4 Layer
- M3 Layer
- 0.5 um
- 0.8 um
- 3.5 mm SiO2
- 250 um
- 5.6 mm Quartz

Image courtesy: IBM
Image courtesy: Samsung
Image courtesy: Infineon
Image courtesy: Georgia Tech
Image courtesy: UCSD

Note that these examples are not necessarily the pioneers of these package technologies for mmWave phased arrays.

Bodhisatwa Sadhu, IBM Research, Fundamentals of mm-Wave Phased-Arrays, ISSCC2022, T10
Examples of Advanced Packaging Techniques for 5G

GaTech: 0.2dB Insertion Loss @ 28 GHz!


HRL: Wafer-Level integration for III-V

S. Nadre, “10um Pitch Bumping of Singulated Die Using a Temporary Metal Embedded Chip Assembly Process,” 2022 ECTC
Highly Integrated D-Band Phased-Arrays for 6G wireless Communications

A 140 GHz FEM in 22nm FD-SOI

- **Design**
  - 4-stage PA, LNA
  - Asymmetric T/R Switch with T/L
  - ESD robustness
  - Stacked-FET PA
  - Gain boosting technique
  - Backgate terminated with 15KV R to enhance linearity and PAE
- **Results (including switch loss)**
  - **Tx:** 33.6 dB Gain, 12.5 dBm Peat, 10.8% PAE max
  - **Rx:** 20 dB Gain, 9.2 dB NF, 20mW

Radio-On-Glass Technology

- Glass is used as an interposer
- Carrier DC, digital and RF
- integrated SIW waveguide
  - Low loss (0.04 dB/mm)
  - Conversion from GSG to SI
  - SIW to WR-6 conversion
- PCB carries baseband interface
- LO interface for both chips

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Mohamed Elkhouly, Shahriar Shahramian, Nokia: ISSCC 2022, 6G Forum

What is the breakpoint for AiP versus AoC? And for 2.5D versus 3D?
The 3D Interconnect Technology Landscape

**3D-SIP**
- Package stacking
  - Multi-die Packaging
  - Interposer “2.5D”
  - Embedded Die

**3D-SIC**
- Die Stacking µbump

**3D-SOC**
- Wafer-to-Wafer bonding
- Wafer-to-Wafer Sequential Processing

**3D-IC**
- Transistor Stacking

3D Interconnect Pitch scaling:
- 1mm
- 400µm
- 100µm
- 40µm
- 20µm
- 10µm
- 4µm
- 2µm
- 1µm
- 500nm
- 100nm

3D Interconnect Density (#/mm²):
- $10^1$
- $10^2$
- $10^3$
- $10^4$
- $10^5$
- $10^6$
- $10^7$
- $10^8$

Nadine Collaert, imec, Emerging device and heterogenous integration technologies for sub-THz Applications, ISSCC 2022, 6G Forum.
Technology/Capability Gaps and Showstoppers

Challenge 2: Selection of Semiconductor Technology Based on Output Level

5G Application Scenarios & Requirements 2018 (estimated)

<table>
<thead>
<tr>
<th></th>
<th>Handset</th>
<th>Access point</th>
<th>Base station</th>
<th>Backhaul</th>
<th>Last mile</th>
</tr>
</thead>
<tbody>
<tr>
<td>EIRP (ave)</td>
<td>30 dBm</td>
<td>43 dBm</td>
<td>60 dBm</td>
<td>60 dBm</td>
<td>75 dBm</td>
</tr>
<tr>
<td>Number antennas</td>
<td>4-6</td>
<td>32</td>
<td>256</td>
<td>256</td>
<td>256</td>
</tr>
<tr>
<td>Pave / PA</td>
<td>14 dBm</td>
<td>11 dBm</td>
<td>10 dBm</td>
<td>10 dBm</td>
<td>25 dBm</td>
</tr>
<tr>
<td>Pmax/PA</td>
<td>23 dBm</td>
<td>20 dBm</td>
<td>19 dBm</td>
<td>19 dBm</td>
<td>33 dBm</td>
</tr>
<tr>
<td>Efficiency (ave)</td>
<td>20%</td>
<td>20%</td>
<td>20%</td>
<td>20%</td>
<td>20%</td>
</tr>
<tr>
<td>DC power</td>
<td>0.6 W</td>
<td>2 W</td>
<td>12 W</td>
<td>12 W</td>
<td>390 W</td>
</tr>
</tbody>
</table>

Estimated Power Ranges for 5G TX ICs & Estimated Max Power of Different Technologies

[Graph showing power ranges for 4G and 5G technologies]
Necessary Semiconductor Technologies for 6G

- **Objective**
  - Support high data rate Communications
  - Spatial multiplexing for high capacity

- **Benefits (140 – 1000 GHz)**
  - Large available spectrum
  - Shorter wavelength – more channels for same sized array

- **Challenge**
  - Atmospheric attenuation
  - PAA element spacing - $\lambda/2$ @ 150 GHz is 1 mm
  - Challenging packaging technologies

- **Technologies**
  - **III-V: InP HBT, InP HEMT, GaN HEMT, SiGe**
    - Heterogeneous Integration
    - Small Form Factor
    - Antenna On Chip

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Nicholas Comfoltey, “Emerging Device Technologies for RF/mmWave FEMs,” ISSCC2023 Forum
Next Stop For R&D: 6G


144 GHz TX beamformer module with eight dual-channel 45nm RFICs wire bounded to the antenna array. (Samsung)

Antenna array with 16 RF channels at 144 GHz carrier frequency.

Antenna pattern shows 21 dB of realized gain and +/-40 degree steerability.

Promise of 5G

5G will expand the mobile ecosystem to new industries

- Precision agriculture
- Construction and mining
- Digitized education
- Connected healthcare
- Richer mobile experiences
- Smart manufacturing
- Intelligent retail
- Smart city

Powering the digital economy

$13.1 Trillion in global sales activities by 2035

6G will bring new and enhanced user experiences across the connected intelligent edge.

6G 140-GHz Phased Array

Antenna on Quartz Superstrate

- Patch antenna arrays fabricated on the quartz superstrate
- EM wave coupled between the on-chip feed and the antenna
- Antenna feed matching network based on microstrip TL

Build Phased-Array Systems at 140 GHz

Method: Wafer-Scale with Quartz Superstrate (Used above 60GHz)

<table>
<thead>
<tr>
<th>Pros</th>
<th>Cons</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low-cost carrier PCB</td>
<td>More chip-level design effort</td>
</tr>
<tr>
<td>Only IF and LO distribution, SPI, VDD on PCB</td>
<td>Antennas may not be wideband</td>
</tr>
<tr>
<td>Can be used at high frequency</td>
<td>Possible air gap between Quartz and silicon</td>
</tr>
</tbody>
</table>

RX Meas
Li & Rebiez, "A 140GHz CMOS RFSoI Transmit-Receive Phased-Array Wireless Link with 11–12Gbps and 16 and 64-QAM Operation,” IMS2022
Enabling technologies, 6G new application opportunities and technological challenges

- RF spectrum for future localization and sensing systems
  - Leap in available bandwidths and carrier frequencies
- The transition to THz frequencies has several important benefits.
  - Signals at these frequencies are unable to penetrate objects, leading to a more direct relation between the propagation paths and the propagation environment.
  - At higher frequencies, larger absolute bandwidths are available, leading to more resolvable multi-path in the delay domain with more specular components.
  - Shorter wavelengths imply smaller antennas, so that small devices can be packed with tens or hundreds of antennas, which will be beneficial for angle estimation.
  - The high-rate communication links offered by 6G will be able to be leveraged to quickly and reliably share map and location information between different sensing devices.

- 6G is not just new frequency bands – it will be AI-enabled for sensing, communications and imaging
**6G Spectrum Extension**

- 5G NR supports frequency bands up to 52.6 GHz, and extension to approximately 90 GHz for future release.
- 6G exploits higher frequency bands than 5G such as “millimeter wave” and “terahertz wave” (~300 GHz), and remarkably wider bandwidth can achieve extreme high data rates exceeding 100 Gbps.

http://6gglobal.org/download/2-1.%20NAKAMURA,%20Takehiro.pdf
Summary

• We are at a unique point in time when there is a global recognition on the critical roles of semiconductor and microelectronics as foundational pillars to nations economies.

• There is immense need for a Heterogeneous Integration technology roadmap addressing future vision, difficult challenges, and potential solutions to pave the way for Microelectronics Resurgence.

• Our Greatest Challenge are ourselves: will we take full advantage of unique opportunities today collaboratively advancing the science & technology for the benefit of humankind.

• Heterogeneous integration (e.g SiP & Chiplets & more) is a broad & deep base for Science & Technology Renaissance & Microelectronics Resurgence.
Thank You!

Backups